AD-763 711

PROTOTYPE FOR A LOW COST LASER GUIDANCE UNIT FOR A BDU-33 PRACTICE BOMB

William C. Ayers

Air Force Institute of Technology
Wright-Patterson Air Force Base, Ohio

March 1973

DISTRIBUTED BY:

NTIS

National Technical Information Service
U. S. DEPARTMENT OF COMMERCE
5285 Port Royal Road, Springfield Va. 22151

PROTOTYPE FOR A

LOW COST LASER GUIDANCE UNIT

FOR A BDU-33 PRACTICE BOMB

THESIS

GAW/MC/73-2 William C. Ayers
Capt USAF

UNCLASSIFIED
Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Air Force Institute of Technology (AU) Wright-Patterson AFB, Ohio 45433	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE
Prototype for a Low Cost Laser Guidance Unit for a BDU-33 Practice Bomb

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

5. AUTHOR(S) (First name, middle initial, last name)
William C. Ayers
Captain USAF

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
March 73	~~60~~ 68	13

8a. CONTRACT OR GRANT NO.	9a. ORIGINATOR'S REPORT NUMBER(S)
b. PROJECT NO.	GAW/MC/73-2
c.	9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)
d.	

10. DISTRIBUTION STATEMENT

Approved for public release: distribution unlimited

11. SUPPLEMENTARY NOTES Approved for public release; IAW AFR 190-17 Jerry C. Hix JERRY C. HIX, Captain, USAF Director of Information	12. SPONSORING MILITARY ACTIVITY Air Development & Test Center Applied Physics Division Eglin AFB, Florida 32542

13. ABSTRACT

Training is required if laser-guided weapons are to be used effectively, but the cost when utilizing the full scale weapon is prohibitive. This report describes a prototype for a low cost ($140) laser guidance unit designed to be used in conjunction with a BDU-33 practice bomb. This unit, completely self contained, can be dropped from the SUU-20 practice ordnance dispenser. It utilizes the same type laser illuminator and has a guidance logic similiar to the standard laser guided bomb and therefore provides realistic training. The unit could be used for low cost and effective laser-guided weapons training.

DD FORM 1 NOV 65 1473

UNCLASSIFIED
Security Classification

UNCLASSIFIED
Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Laser Guidance Unit						
Lasers						
Guided Bomb						

UNCLASSIFIED
Security Classification

GAW/MC/73-2

PROTOTYPE FOR A LOW COST LASER GUIDANCE UNIT FOR A BDU-33 PRACTICE BOMB

THESIS

Presented to the faculty of the School of Engineering

of the Air Force Institute of Technology

Air University

in Partial Fulfillment of the

Requirements for the Degree of

Master of Science

by

William C. Ayers

Capt USAF

Graduate Air Weapons

March 1973

ic

Preface

If the Air Force is going to continue to develop sophisticated and costly weapons, then inexpensive methods for effective aircrew training must also be developed. During my tour in Vietnam I observed that one of the best of the new tactical weapons was the laser guided bomb. However, other than by dropping full scale bombs, no means was being provided for the initial or continuation training of aircrews. My goal, which I achieved, was to build an inexpensive laser guidance unit for a BDU-33 practice bomb. It was an extremely interesting project because I had to establish a "mini-SPO" in order to accomplish this task. Building this device demanded knowledge of such diverse fields of science as mechanics, physics, electronics, and aerodynamics. I experienced all the headaches involved with procurement delays, facility delays, and lack of funds. I gained a great deal of insight into the problems involved in the building of a new weapon and also at the same time some good practical engineering experience.

I wish to express appreciation to my thesis sponsor Dr. Henry Register of the Applied Physics Division of ADTC, Eglin AFB, for all the support that he and his personnel provided. It would have been extremely difficult to complete this project without their aid. Dr. Peter Torvik, my thesis advisor, I thank for keeping me headed down the path to success when I could see no light at the tunnel's end. Finally, I would like to thank my wife, Kris, for her support during these two long years of schooling.

William C. Ayers

Contents

Contents

List of Figures

List of Figures

List of Tables

Abstract

Training is required if laser-guided weapons are to be used effectively, but the cost when utilizing the full scale weapon is prohibitive. This report describes a prototype for a low cost ($140) laser guidance unit designed to be used in conjunction with a BDU-33 practice bomb. This unit, completely self contained, can be dropped from the SUU-20 practice ordnance dispenser. It utilises the same type laser illuminator and has a guidance logic similiar to the standard laser guided bomb and therefore provides realistic training. The unit could be used for low cost and effective laser-guided weapons training.

PROTOTYPE FOR A LOW COST LASER GUIDANCE UNIT FOR A BDU-33 PRACTICE BOMB

I. Introduction

In looking to the future one should consider the past. Toward the end of WW II, guided bombs had been developed and were entering the tactical inventory. However, development of these guided weapons completely ceased at the end of that war. Hopefully, after SEA, we will not make the same mistake but will continue to develop laser guided weapons. If this is to be accomplished, an adequate training program must be developed and maintained. By training, the idea is kept alive and useful operational feedback is provided for continued weapon development. This report describes the design and manufacture of a laser guided practice bomb. Section II explains how an inexpensive laser guided practice bomb would be an aid to training. Judgement of crosswind effects, complicated reflection patterns, and training in specialized laser bombing techniques can not be accomplished except by utilizing a bomb that will guide. Section III details the theory of operation that the guidance unit will utilize. In almost all respects, it simulates the guidance of the full scale weapon. Section IV gives step by step instructions for building the laser guidance unit. It specifies the materials and techniques used in construction. Section V lists some ideas

which might be used to improve the guidance unit, but which could not be investigated because of a shortage of time.

All necessary technology is currently available. The task will be to select the least expensive and most innovative way to implement this technology. With this in mind, every possible effort was made to utilize "off the shelf" hardware items or, at least, items that require very little labor, especially specialized labor, to produce.

II. Benefits To Training

With the introduction of the laser-guided bomb (LGB) in the South East Asian conflict, there was a significant increase in tactical bombing accuracy. Bombs could be dropped with nearly pin-point precision and thus fewer missions were required for a specific task. However, there were many LGB misses and a large percentage of these misses were attributed by PACAF to a lack of sufficient aircrew training. The problem with providing more training is the expense associated with laser-guided bombs which cost about $4,000. This cost may be acceptable during a war because most of the training can be accomplished on actual missions to lightly-defended targets. During peacetime this cost will probably not be acceptable. Yet, as with all weapons, training must be provided if one expects the aircrews to remain proficient. As an example, it would cost in excess of $4,000,000 to allow each aircrew in a Wing to drop ten LGB's per year. This allows each aircrew to drop less than one bomb per month, hardly sufficient. Some of the problem areas encountered in dropping laser-guided weapons that could be overcome by adequate practice are:

I. Judging Crosswind Effect: Not only does the bomb drift with the crosswind but the seeker suffers misalignment relative to the ballistic trajectory, thus, compounding the drift problem since the seeker is not looking directly at the target.

2. Judging Different Target Reflectivities: Constituents of the atmosphere such as water or dust can absorb or scatter large amounts of the laser energy making successful bombing impossible. The scattered energy can produce false targets. Each target will have a complicated reflection pattern. These reflection patterns can be anticipated by a trained aircrew.

3. Co-ordination Between Aircrew Members: All laser-guided weapons are dropped by multi-crew aircraft, usually an F-4. Sometimes the designating aircraft is not the dropping aircraft. This last technique requires special co-ordination and practice.

4. Specialized Techniques: Designator aircrew members (WSO) have developed specialized techniques for dropping against caves, moving trucks, underwater portages, AAA sites, etc. These techniques must be taught to the inexperienced aircrew.

5. Release Basket: The release "basket" is a relatively complicated function of the geometric positions of the laser and weapon release aircraft, target conditions, and atmospheric conditions. The ability to properly release the weapon so that it will guide to the target must be taught to the inexperienced aircrew by practice. There are not many aircraft references, and experience is the only way to learn.

6. Target Tracking: Many times the laser beam is pulled off the target by the evasive maneuvering of the aircraft during pull out. WSO's need frequent practice in holding the beam on the target during evasive maneuvering.

All of these problem areas can be overcome by providing adequate practice to the aircrew. (Ref 2:35).

The proposed TAC concept for LGB training is centered around having the WSO practice holding the designator energy on the target while the aircraft commander drops a BDU-33 unguided practice bomb from ten thousand feet. Although this method certainly is inexpensive, not all the training objectives mentioned in paragraphs 1-6 can be met.

This current TAC concept will provide a satisfactory means for initial WSO training and at the same time provide the A/C with conventional bombing practice from a high altitude. This concept would provide a satisfactory Phase I training. However, it does not provide that immediate, positive feedback so necessary for judging crosswind effect, complicated reflection patterns, nor does it provide a means for teaching those specialized techniques mentioned in paragraph 4. How can the aircrew be sure that, utilizing their technique, the bomb would have really guided on the reflected laser energy, especially on a tactical range? How can the aircrew be sure the crosswind offset was enough? These

items of finesse in dropping LGB's can only be taught by dropping bombs that will actually guide. A low cost laser-guided practice bomb would provide these necessary Phase II training objectives at an economically feasible cost.

The problem is to provide an inexpensive "practice" laser-guided bomb for aircrew training. Currently TAC uses a small, inexpensive, practice bomb (BDU-33) for unguided bombing training. The proposed solution to the problem is to design and build an inexpensive modular guidance unit which can be attached to the BDU-33, thus converting it into a low cost practice laser-guided bomb. This modification of the BDU-33 should not interfere with its carriage in the SUU-20 or SUU-21 practice bomb dispenser.

The practice bomb modification unit must closely simulate the performance of the KMU-351 modification kit. There are three conditions which must be satisfied for a successful LGB or practice LGB drop. The first condition is that the target must be within the 24° field of view of the seeker assembly. The second condition is that the bomb must be dropped at a point which is within the aerodynamic envelope of the bomb. The bomb can be dropped no further away from the target than the maximum glide range nor no closer to the target than the maximum drag possible as shown in Figure 1. (Ref 11:20). The third condition is that the bomb must receive sufficient energy for guidance. These conditions define the release point.

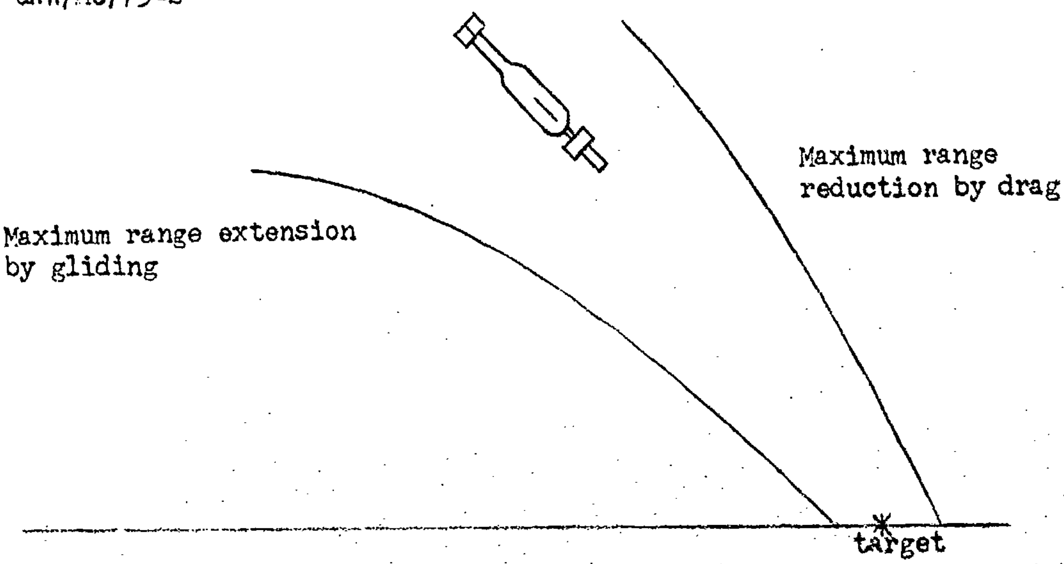


Fig. 1. Aerodynamic Drop Basket

This design need not provide guidance for any laser radiation pulse patterns other than those that are presently in use in the Paveway or Paveknife laser designators. It is really not necessary that the practice bomb accomodate all pulse repetition codes. The following assumptions which bear on training with guided bombs are made:

1. A 5% to 10% reduction in reliability when compared to the present full size bomb would be acceptable in order to realize giant cost savings ($4,000 per bomb reduced to $140). This reduction in reliability may not be necessary.

2. By keeping the bomb's center of gravity at approximately the same location where will be no appreciable change in its ballistic characteristics. These characteristics are needed only for the first 2-3 seconds of the drop (safe separation time). After that guidance is available.

III. Theory of Operation

One of the best ways to understand the theory and operation of this laser guidance unit is to follow the reflected laser pulse as it is processed thru the guidance unit of the LGB.

When the reflected pulse reaches the bomb, the signal is processed as in Figure 2.

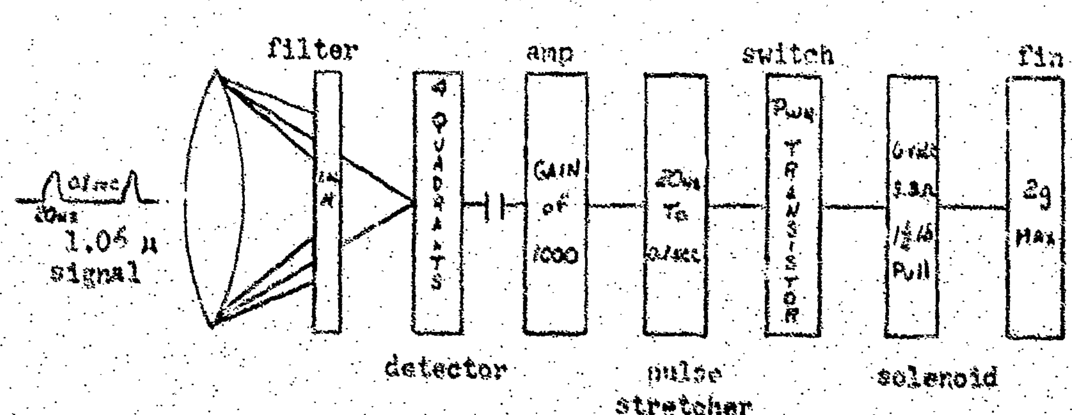


Fig. 2. Guidance Signal Flow

The signal, as shown in Figure 2, is focused on the detector by the collecting lens. The 1.06 μ filter prevents the detector from being activated by ambient sources. The detector is coupled to the amplifier by a capacitor. This capacitor isolates any D.C. noise from the rest of the circuit. After

being amplified, the signal must be stretched from 20 nanoseconds to one tenth of a second in order to keep the switch from oscillating. The closing of the switch, a transistor, provides power to the solenoid. When the solenoid activates, it rotates a canard fin into windstream. This fin rotation provides a guidance correction for the bomb's flight path.

A schematic diagram of the completed design is included in Appendix A and can be folded out and used as a visual aid in following the signal path. The guidance signal originates from a high peak power, short (20 nanosecond) pulsed laser which is usually aircraft mounted. This laser (called a designator) is aimed and fired at the desired target. Because of the high peak power rating of this laser (usually greater than 10^6 watts) a large amount of this power will be reflected by the target. The magnitude of this reflection as seen by the LGB will be a function of target absorptivity and geometry, grazing angle, atmospheric absorptivity, bomb altitude, and how accurately the bomb was dropped. (Ref 3:46). Grazing angle is defined as the angle between the laser beam centerline and the horizon as shown in Figure 3. Low grazing angles cause pulse stretching and reflection of the energy in a direction opposite that necessary for bomb guidance. (Ref 11:31).

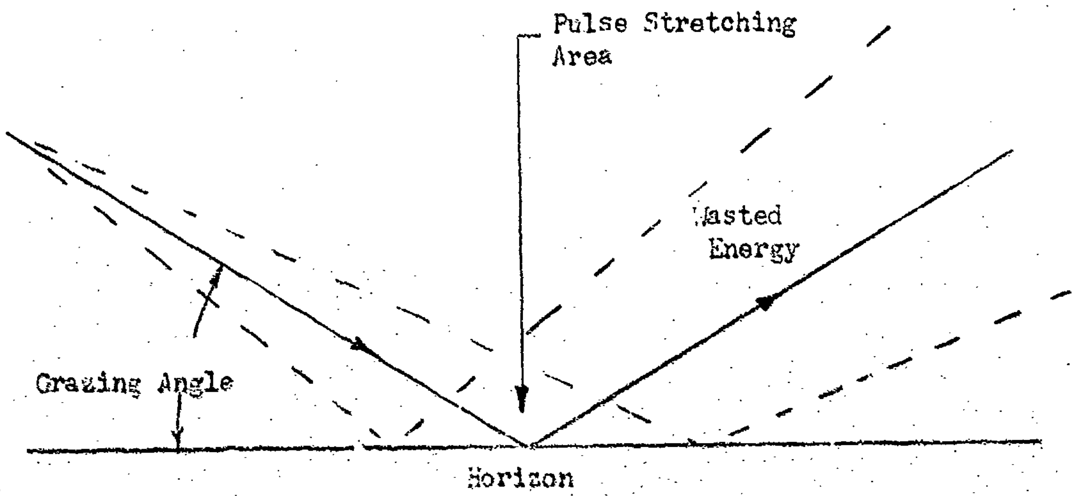


Fig. 3. Grazing Angle

The laser energy is collected by an objective lens and focused onto a detector. This lens is mounted in a finned probe. The probe is attached to the front of the LGB by a universal gimbal which is attached to the probe at the probe's center of gravity (cg). Mounting the probe at its cg allows it to be statically balanced for aircraft carriage and at the same time significantly reduces dynamic oscillations which might destroy it during the bomb's fall.

This gimbal also allows the probe and the bomb to oscillate independently of each other during the bomb's descent. The longitudinal axis of the probe is designed to fly always aligned with the relative wind, within gimbal limits of $\pm 15^{\circ}$. Due to bomb assymetry, the bomb's longitudinal axis probably

will not fly aligned with the relative wind. The probe does roll with the bomb. By always flying aligned with the relative wind, the probe provides a stabilized reference platform for the detector from which the bomb's relative position to the target can be determined. Each quadrant of the detector in the probe corresponds to a specific fin rotation direction and therefore a specific guidance command. When the reflected laser energy is focused on a specific quadrant, a signal is generated which is electronically processed into a guidance command as shown in Figure 4.

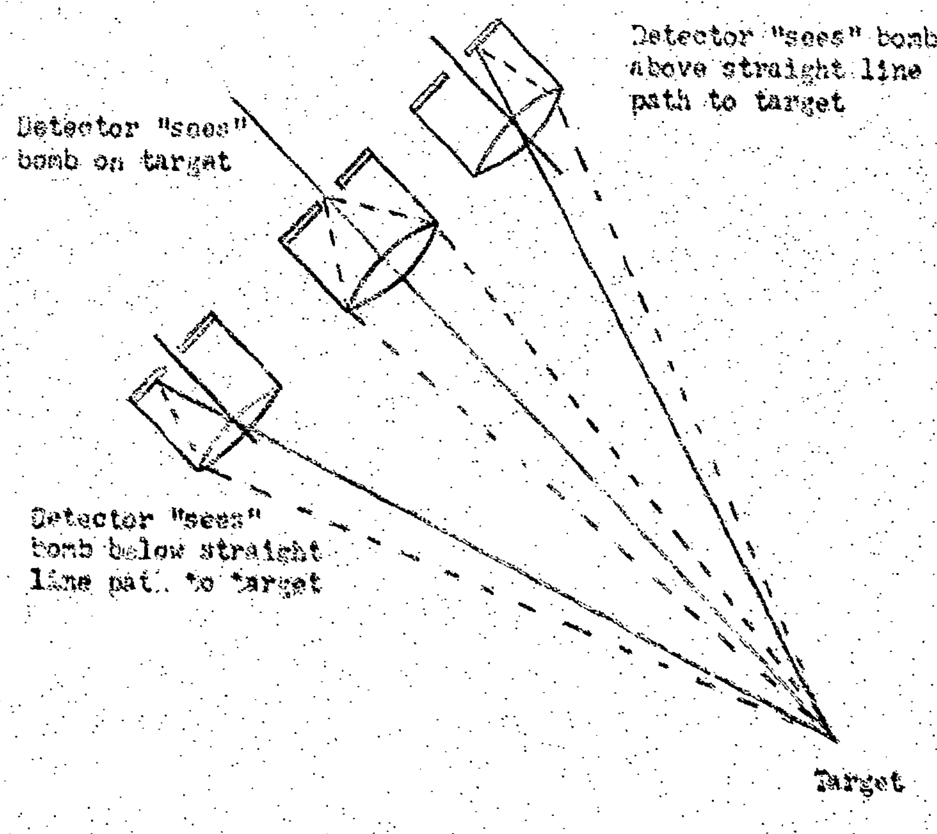


Fig. 4. Guidance Logic

It is important here to note that once the bomb starts to guide it attempts to fly a straight line to the target. The bomb does not succeed in flying a straight line due to its simplistic guidance scheme in which any need for guidance correction causes a full deflection of the guidance fins. This method is nicknamed "Bang-Bang" guidance. The two dimensional representation of the flight path profile when utilizing "Bang-Bang" guidance tends to be as shown in Figure 5.

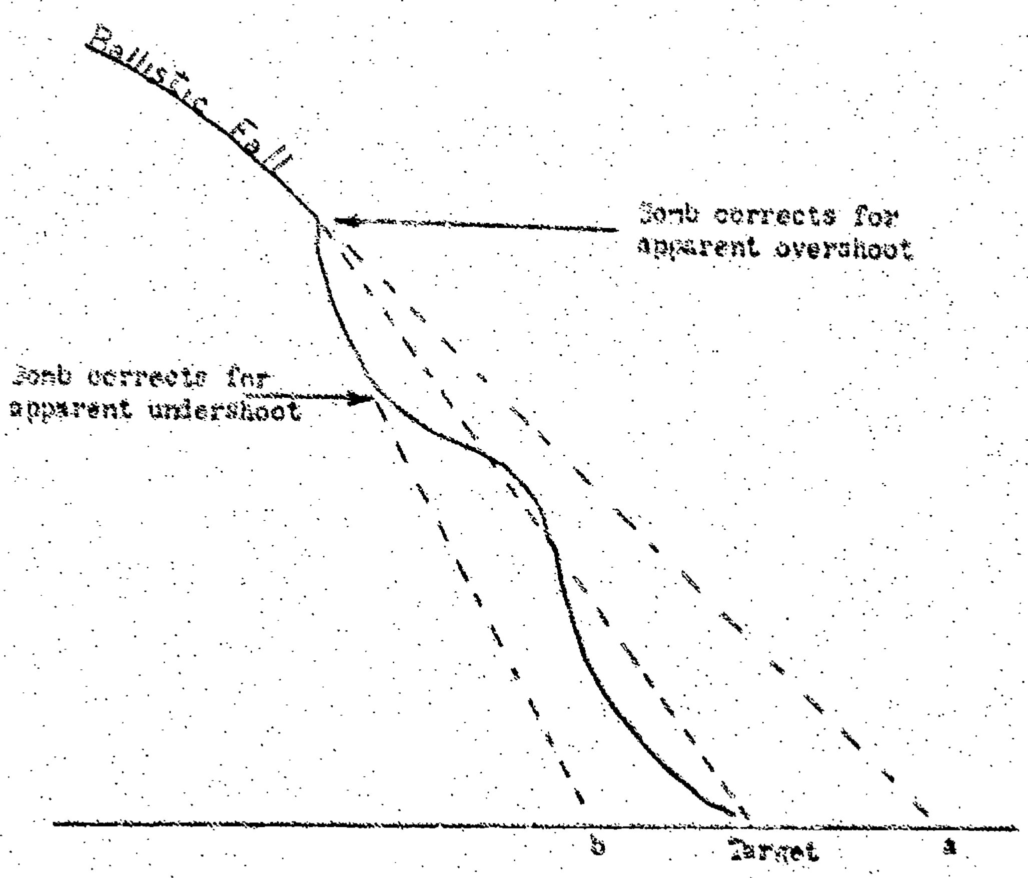
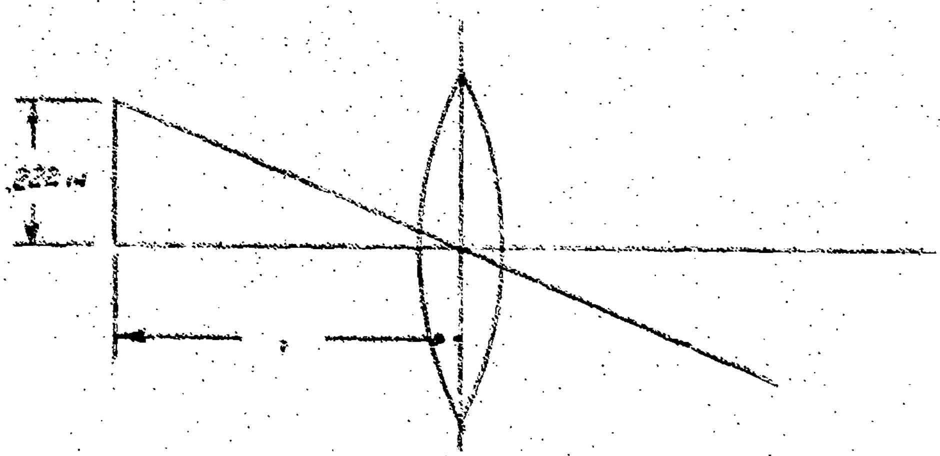


Fig. 5. Typical LGB Flight Profile

After a short ballistic fall (2-3 seconds) which provides safe separation from the aircraft, the laser bomb begins to guide on the target. The probe is aligned with the relative wind and therefore the seeker initially "looks" along a line tangent to the ballistic path as shown in path a of Figure 5. The seeker perceives the target to be below this tangent line and therefore corrects the bomb path to achieve a straight line intercept of the target. However, due to the "Bang-Bang" guidance the bomb will overshoot this desired goal as shown in path b of Figure 5. The rest of the bomb's fall is a series of oscillations about the original straight line from the end of the ballistic drop to the target. (Ref 7:41).

Optics

The full scale bomb has a field of view of 24°. Geometric optics, as shown in Figure 6, is used to calculate the lens focal length (f) necessary for the prototype to have the same field of view as the full scale LGB.



$$\tan 12^\circ = .222/f \tag{1}$$

$$f = 1.04 \text{ inches} \tag{2}$$

Fig. 6. Determining f of Lens

The active area of the detector in the prototype has a radius of .222 inches. Using this and the desired field of view (half angle 12°) the collecting lens focal length becomes 1.04 inches. Between the collecting lens and the detector is a multi-layer interference filter which transmits only that energy very near 1.06 micrometers. The bandpass of this filter is around .03 micrometers.

The multi-layer interference filter consists of several layers of dielectric material having an thickness of ¼ wavelength. These layers are vacuum deposited on a glass substrate. The dielectric material in these layers alternates from higher to lower indicies of refraction. The purpose of this alternation is to produce destructive interference between the beams reflected at each interface. This is achieved by having the reflections occur at less dense to more dense interfaces and having a π phase shift result from propagation in the second medium. The layer thickness (d) in a medium (n) can be calculated from

$$d_L = \lambda_o / 4 n_L \tag{3}$$

$$d_H = \lambda_o / 4 n_H \tag{4}$$

The peak transmission occurs at λ_o . The bandpass of the filter depends on the quality and the number of layers. The more layers the more destructive interference and the less reflection at λ_o . By using a narrow bandpass optical filter one eliminates most of the noise caused by the detector responding to ambient light. A filter is usually designed for normal incidence. As the radiation is tilted from the normal, the effective filter wavelength is shortened. For a tilt up to 12° from the normal, this effect is negligible. Higher temperatures, above 20°C, will lengthen the effective wavelength and lower temperatures will shorten the effective filter wavelength. Figure 7 shows a typical design and the transmission curve for a multi-layer filter. Typical filter efficiencies are 60% to 70%.

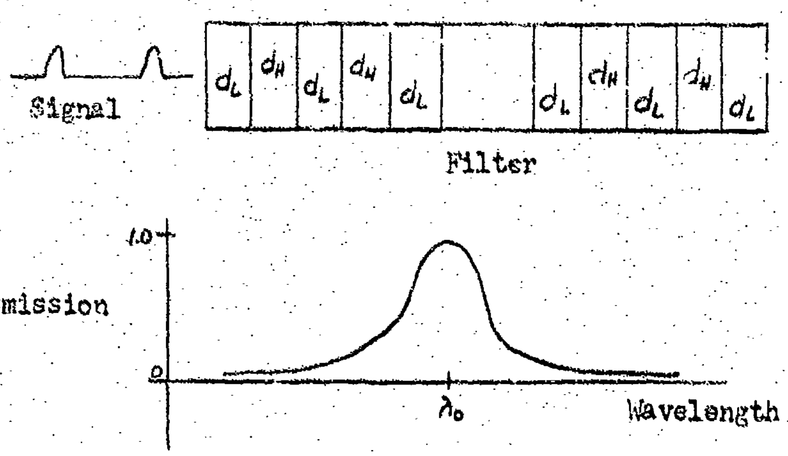


Fig. 7. Transimission Curve for Multi-Layer Filter

Detector

A quadrant silicon detector is nothing more than four diodes. The detector is reverse-biased and therefore operates in the photoconductive mode (ie, it generates current, not emf, when illuminated). (Ref:Appendix A). This current signal which is negative with respect to ground, is coupled to the amplifiers thru a capacitor as shown in Figure 10. The detector quadrants and the guidance fins are aligned as shown in Figure 8.

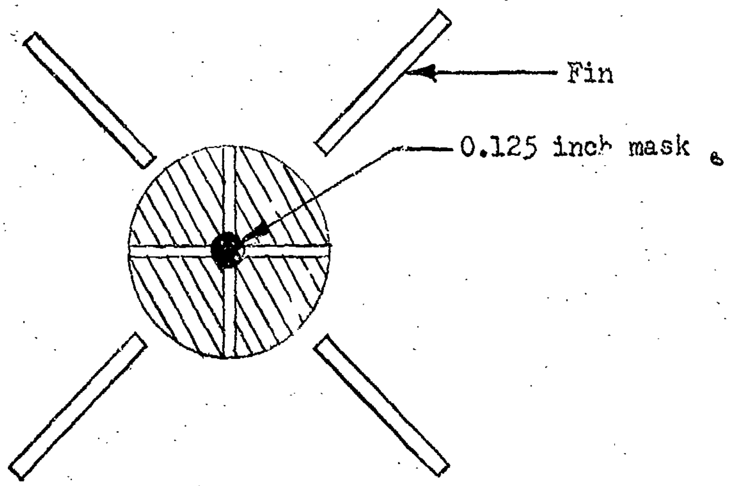


Fig. 8. Quadrant Silicon Detector & Fin Alignment

Each quadrant is electronically isolated from the others. If radiation over a 0.35 to 1.13 μ bandwidth is incident on the surface of the detector, a small current will flow which is proportional to the input signal up to the saturation level. The spectral sensitivity of the detector will generally vary with

wavelength across the spectral bandwidth of the detector. At 1.06 μ, a silicon detector has a quantum efficiency of about 50% of that available at 0.9 μ. Peak sensitivity and output for a specific wavelength will be achieved when the incident light is normal to the diode. There will be some pulse width stretching thru the silicon detector since the detector rise time is normally about 5 to 10 nanoseconds.

The center of the detector is masked so that when the focal spot is centered all four fins will not activate simultaneously. The mask is 1.25 x diameter of the spot size to allow for spot jitter. Spot size was experimentally determined to be 0.1 inch. Therefore the mask is 0.125 inch in diameter. The bomb is rolled very slowly (2-4 turns in 10 thousand feet of fall) by a slight bend of the tail fin so as to make it impossible for the focal spot to track the line of intersection between two quadrants for the entire fall time.

At this point one must investigate the minimum signal level to be expected and determine if that signal level is compatible with the detector. A typical designator has an output of 120×10^{-3} Joules in 20×10^{-9} seconds which provides a power of 6×10^{6} watts.

Experiments at the Armament Development and Test Center have shown that, for normal conditions, 50% of the transmitted energy may be lost due to atmospheric scattering and absorption and that tactical target reflectivity is about 33%. Therefore the power available for reflection will be about one megawatt. Now,

if the power is reflected from a target, isotropically through a solid angle of 2π radian, to a bomb at 10,000 feet (normal initial guidance altitude) the signal strength will be as follows:

$$P_R = \frac{P_D}{2\pi R^2} = \frac{10^6 \text{ watts}}{2\pi \times 10^8 \text{ Ft}^2} = 0.11 \times 10^{-4} \frac{\text{watts}}{\text{IN}^2} \quad (5)$$

The collecting area of the lens can be calculated to be .785 square inches and therefore the total power collected will be

$$P_c = (.785)\,(.11 \times 10^{-4}) = 8.6 \text{ microwatts} \quad (6)$$

Thus if the losses are 40% thru the lens and filter, one can say that about 3.5 microwatts will be collected and focused on the detector at ten thousand feet altitude. It was determined that the minimum detectable energy for this silicon detector is about 10^{-15} Joules. Converting this minimum energy to power ($P = 10^{-15}$ Joules/10^{-9} sec $= 10^{-6}$ watts) one finds the minimum detectable power for the detector is very close to that which is available. Thus, ten thousand feet will be a threshold altitude and it may be a problem for the detector to "see" this 3.5 microwatt guidance signal during other than perfect conditions. At this point the signal has been collected by a lens oriented

perpendicularly to the ballistic trajectory, focused thru a 1.06 μ filter and detected by a quadrant silicon detector. These three elements of the signal processing sequence are packaged in a unit called the seeker assembly which is mounted in the front of the bomb probe as shown in the fold out. (Appendix A).

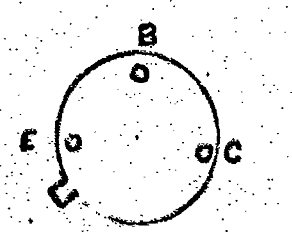
Pulse Conditioning Circuit

The signal must be amplified and stretched to a longer pulse by a R-C circuit (Figure 10). This pulse stretching will provide a DC signal for switching on the solenoid for as long as the 1.06 μ radiation is focused on that quadrant. If the pulse were not stretched, the solenoid and hence the fins would oscillate at 10 pps (the designator pulse repitition rate). After leaving the detector and passing through the isolating capacitor the signal is amplified (gain of 1000) and then stretched from 20 nanoseconds to 0.1 second by the R-C circuit. Thus, as long as a signal is on one quadrant of the detector, the power transistor will be turned on allowing current to flow to the solenoids. There are four of these amplifier-pulse stretcher circuits (one for each detector quadrant).

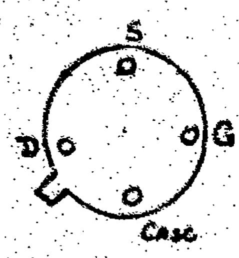
Solenoids

When a circuit is activated it causes a pull-type solenoid to rotate a shaft in a small arc, thus deflecting the fin into the wind stream as shown in Figure 9.

NOTE: Input Pulse is 10ns. at 1 to 5 volts neg. Circuit temp tested for -50°C to 150°C. No oscillation with pulses down to 4 per sec.



HEP 50 & 52



HEP F2005

BOTTOM

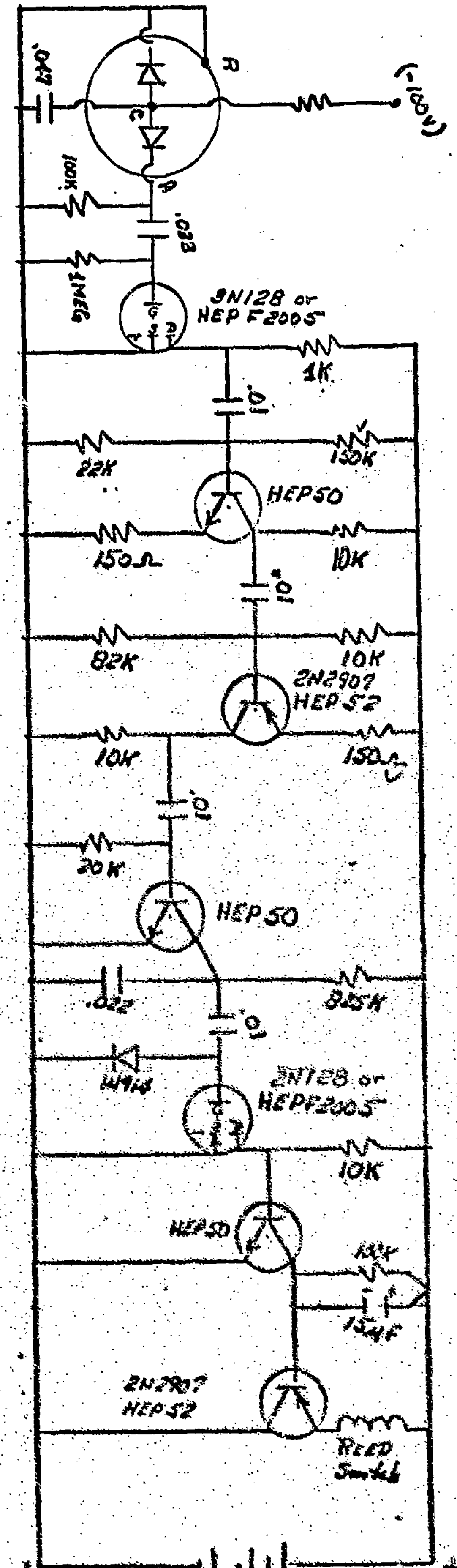


Fig.10. Circuit

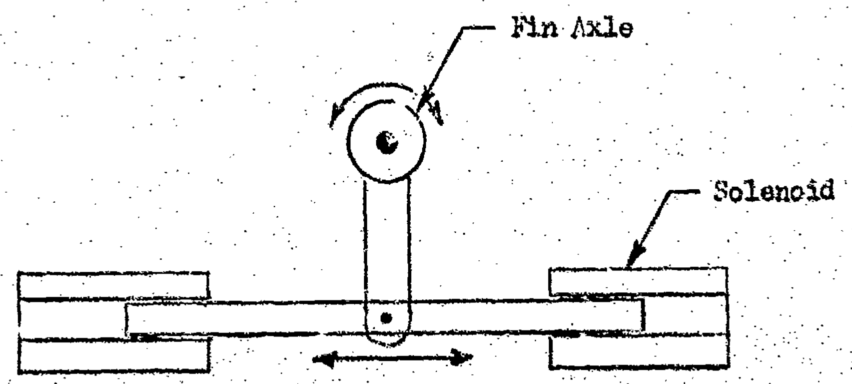
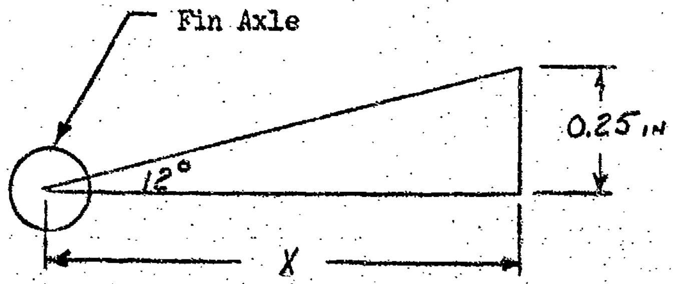


Fig. 9. Fin Rotation Mechanism

By co-locating the center of lift on the canard guidance fin and the canard fin axle, the force necessary to deflect and hold the guidance fins will be small (less than $1\frac{1}{2}$ lb). This is reasonable since the maximum device weight will be about 30 lb and a 2 g maximum guidance acceleration is the most demanded.

Simple geometry was utilized to determine the length of linkage necessary for the solenoid to rotate the fin to 12° angle of attack. The lift curves (C_L vs α) indicated that a 12° angle of attack would provide a good initial correction force and yet leave room for increases in angle of attack without stalling when the bomb begins to correct its heading. The physical size of the main case and the solenoids constrained the solenoid travel to $\frac{3}{4}$ inch. Therefore the situation is as shown in Figure 11.



$$\tan 12° = 0.25/X$$

$$X = 1.20 \text{ inch}$$

Fig. 11. Leverage Sizing

Power for the solenoids is provided by a nine volt lantern battery. Power for the circuit is provided by a small six volt battery. Each circuit is operated from a different battery to prevent coupling of circuits which may lead to circuit oscillation.

Guidance Fins

The fins are mounted on their axles at the fin quarter chord point. The subsonic aerodynamic center of pressure is located at the quarter chord point. By co-locating the guidance fin axle at the fin's quarter chord point, the moment necessary for fin rotation is reduced to that necessary to overcome bearing friction moment, aerodynamic moment and the moments due to the dynamic oscillation of the center of pressure about its static

position at the quarter chord point. After a literature search and discussions with experts in the field, it was decided that the magnitude of these moments would be extremely small when compared to the 1.8 pound-inches provided by the solenoid. However, wind tunnel tests were determined to be the only method to accurately predict the magnitude of these rotation retarding moments. (Ref 10:79).

The full scale bomb and the prototype utilize a maximum of 2 g lift or drag acceleration for guidance corrections. This acceleration is almost normal to the longitudinal axis of the bomb. (Ref 11:21).

The size of the prototype guidance fin was calculated from a static stability analysis. The chart in Ref 8:95 was used to calculate the coefficients of lift (C_l). The aspect ratio (AR) of the canards was taken to be 0.4. With this aspect ratio the fins will not extend excessively and prevent bomb carriage in the SUU-20 dispenser.

Figure 12 shows the bomb's static balance situation and the data known and unknown.

Before starting the analysis it should be remembered that if the bomb's rear fins are flying at an angle, α , with respect to the relative wind, the canards will be flying at $\alpha + 12^{o}$ with respect to the relative wind as shown in Figure 13.

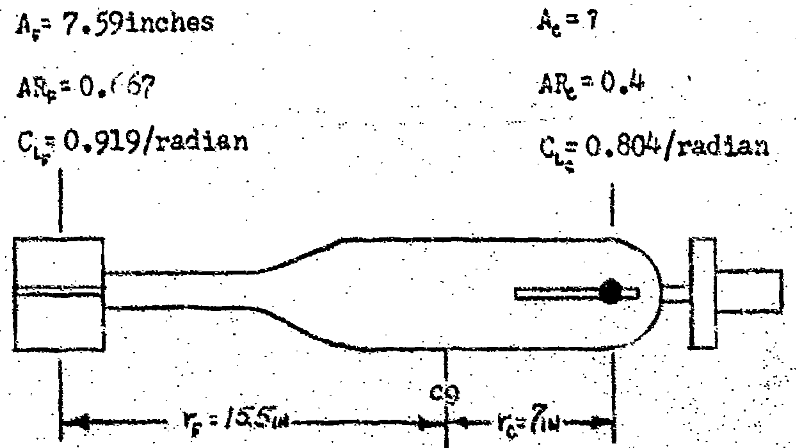


Fig. 12. Bomb Static Stability Analysis

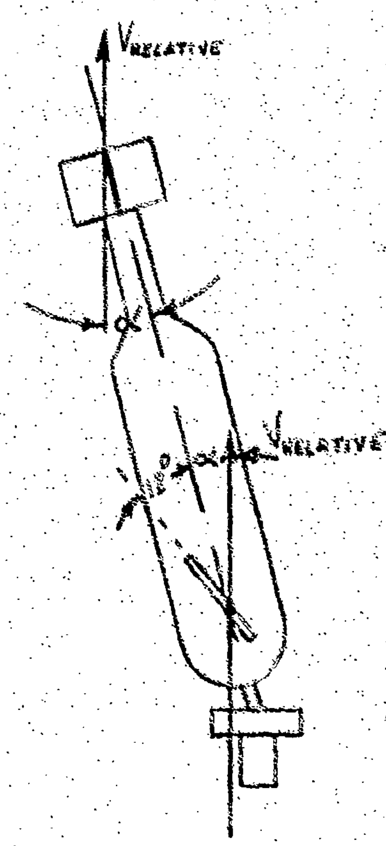


Fig. 13. Angle of Attack Model

The equation for static stability during flight at some angle of attack (α) is:

$$\frac{Lift}{Fin} \times r_F = \frac{Lift}{Canard} \times r_C \tag{7}$$

$$\tfrac{1}{2}\rho V^2 A_F C_{L_F} \alpha\, r_F = \tfrac{1}{2}\rho V^2 A_C C_{L_C} (\alpha + 12^\circ)\, r_C \tag{8}$$

The equation can be reduced to

$$A_F C_{L_F} \alpha\, r_F = A_C C_{L_C} (\alpha + 12^\circ)\, r_C \tag{9}$$

$$108.12\,\alpha = (5.628\,\alpha + 1.179) A_C \tag{10}$$

and is therefore independent of altitude and airspeed.

Canard stall would be disastrous. Therefore, based on the fact that the canard stalls at about 30° angle of attack, (Ref 8; 59) 13° or .226 radians is selected as the static stability angle of attack. Therefore the area of one fin is 10 square inches. With an aspect ratio of 0.4, a 10 square inch fin is 2 inches wide and 5 inches long.

The analysis conditions were 450 kts (518 mph, 760 ft/sec or 19 Mach) and 5 thousand feet (ρ = 0.002 Slugs / Ft^3). The guidance correction force generated by deflecting the fin 12° is:

$$L = \tfrac{1}{2} \rho V^2 A_c C_L \tag{11}$$

$$L = \tfrac{1}{2} (0.002)(760)^2 (0.139)(0.168) \tag{12}$$

$$L = 13.4 \text{ lbf} \tag{13}$$

The guidance fins are spring loaded to the center position, so when the solenoid is switched off the fins automatically return to the neutral position..

The guidance signal has now been completely processed by a guidance unit. A signal on the detector has commanded rotation of a guidance fin.

IV. Manufacture

The objectives in the manufacture of this guidance unit were ruggedness, simplicity and low cost. The guidance unit is for a BDU-33B/B practice bomb (Figure 14). This bomb is 22 inches long, 4 inches in diameter and weighs 25 lb. It is currently used by TAC for unguided bombing training.

Fig. 14. BDU-33 B/B Practice Bomb

Dimensions for the complete guidance unit are shown in Appendix A. The seeker assembly is composed of the collecting lens, optical filter, detector and holder as shown in Figure 15.

The double convex glass lens was acquired from Edmond Scientific Co. (Catalogue No. [illegible],225). It has a 29mm diameter, a 26mm focal length and is uncoated. It costs $1.25 when purchased singly.

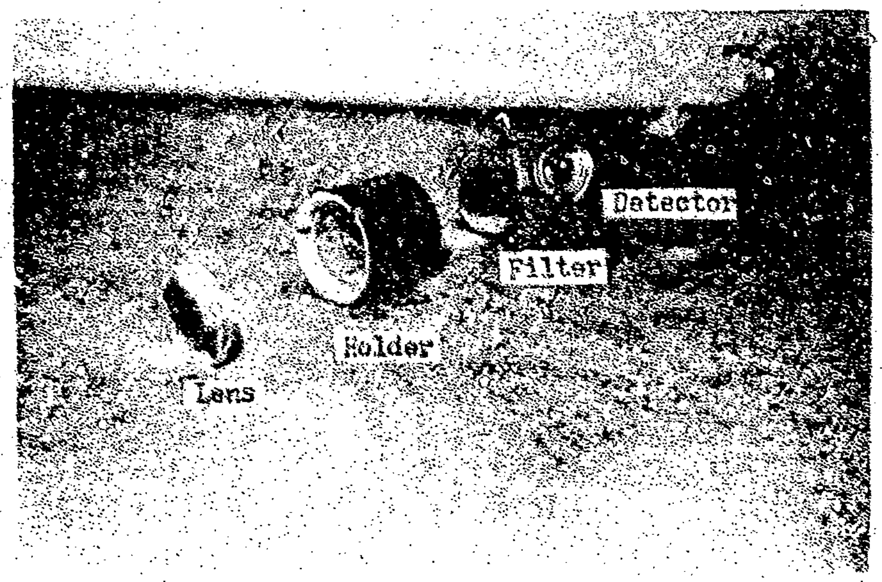


Fig. 15. Seeker Assembly

A 29mm diameter lens, minus the 3.5mm necessary for mounting, leaves an effective 25.5mm (1 inch) diameter collecting lens. This gives a collecting area of .785 square inches. Using a 26mm instead of a 26.6mm (1.04 inch) focal length gives a field of view of 25.1° instead of 26°.

The optical filter was acquired from Optical Coating Laboratory Inc. for a cost of about $9.90 in bulk purchase. It has a bandwidth of about 0.03 micrometers as shown by the spectrograph

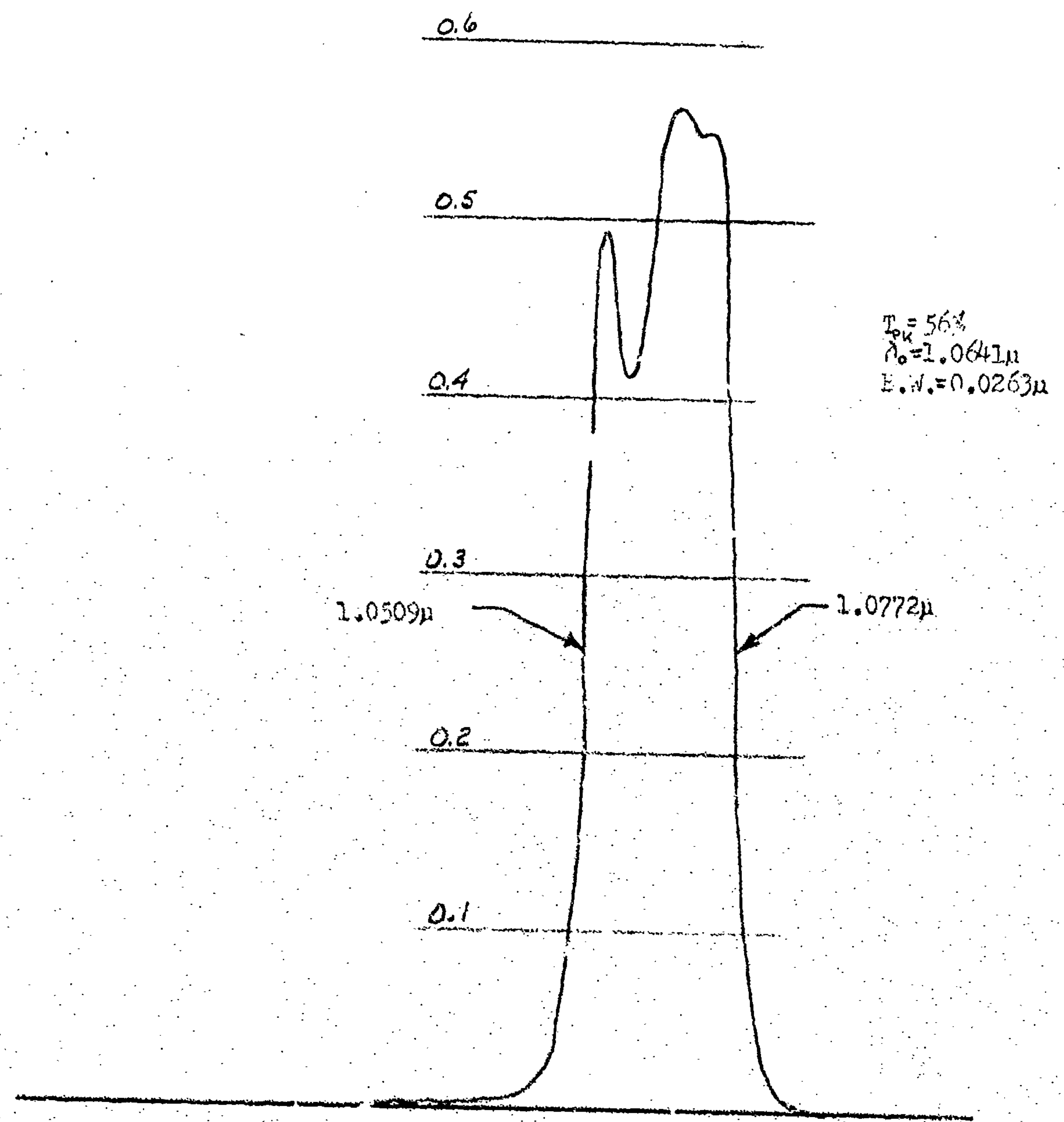


Fig. 16. Transmission curve

analysis of the filter (Figure 16). It is a multi-layer interference filter and functions as described on page 14. The detector was purchased in bulk from EG & G Technology for $65.00. The EG & G detector offers a noise guard ring which increases detector sensitivity. This increased sensitivity is required for this project. The detector is biased by a small 100 volt battery mounted in the main guidance unit case.

The lens, filter and detector are mounted in a holder, as shown in Figure 17, machined from a piece of phenolic.

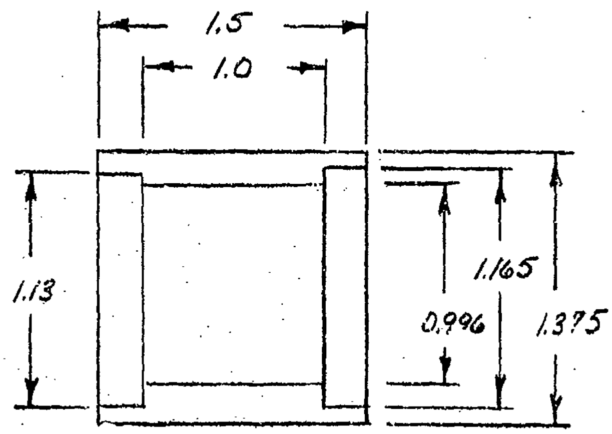


Fig. 17. Holder

There was some concern over the possibility of having to provide an elaborate lens focusing mechanism. However experimentation with the simple holder in Figure 17 proved that the holder was adequate. In the experiment, the holder was mounted in a vise and a circular piece of paper with a pin hole at the

center was placed in either end of the holder as shown in Figure 18.

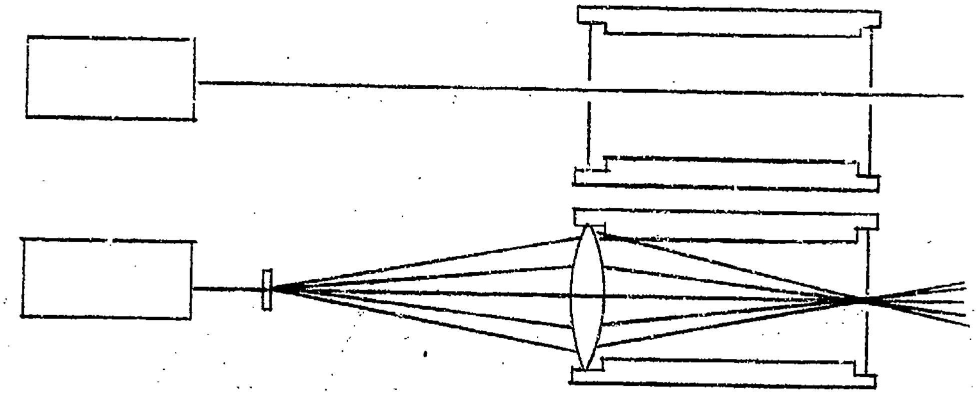


Fig. 18. Holder Validation Experiment

A He-Ne laser was then aligned with the holder until its beam passed thru both pin holes. The beam was now aligned with the center axis of the holder. The front piece of paper was removed and the lens substituted. The laser beam was diffused and reactivated. The resultant focal spot from the collecting lens was focused thru the rear pin hole. This indicated that as long as the lens is mounted perpendicular to the holder, the focal spot will be properly aligned. Moving the lens in and out as much as 1/8 inch produced very little change in the focal spot size. Therefore the spacing between the lens and detector was determined not to be too critical. In fact, it was decided to place the detector slightly inside the focal length in order to increase the spot size. Thus, if the spot were straddling

two quadrants, both quadrants would command guidance simultanously and provide the proper vector direction for optimum bomb guidance. The suggested method of mass producing these holders would be plastic molding using a suitable plastic.

The seeker assembly is mounted in the gimbaled probe. The probe body is a five inch long piece of 1.5 inch O.D. thin walled aluminum tube. The probe tail fins were cast from epoxy resin. The fin (Figure 19) is 4 inches in diameter and 1 5/8 inches thick and was fracture tested by dropping it from a 20 foot height. The fin is epoxy-glued to the aluminum body. The leading edge of the fin is sharpened to achieve decreased drag and increased stability. The entire probe can be mass produced as one piece from a plastic mold.

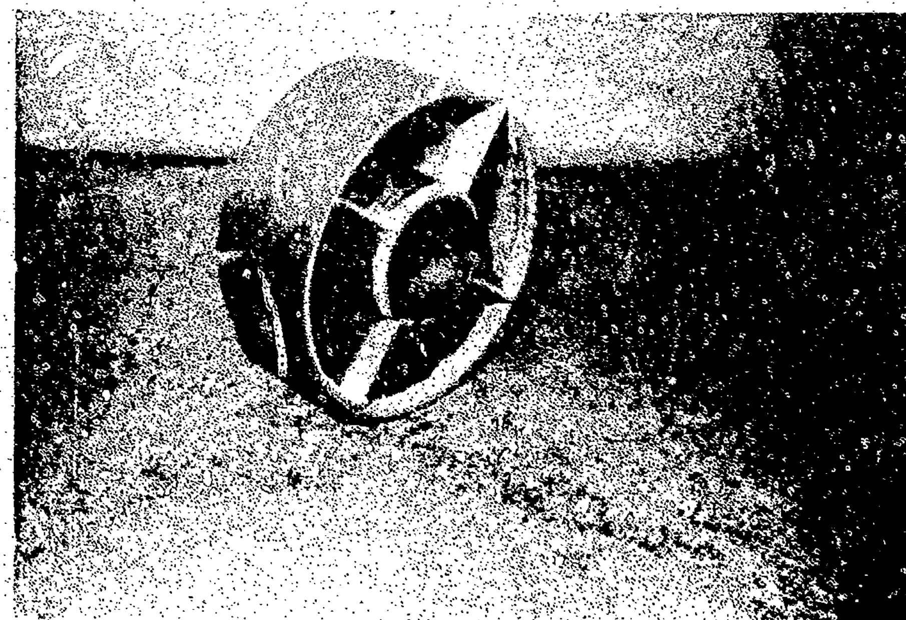


Fig. 19. Probe Fin

The probe is attached to the bomb by the universal gimbal shown in Figure 20.

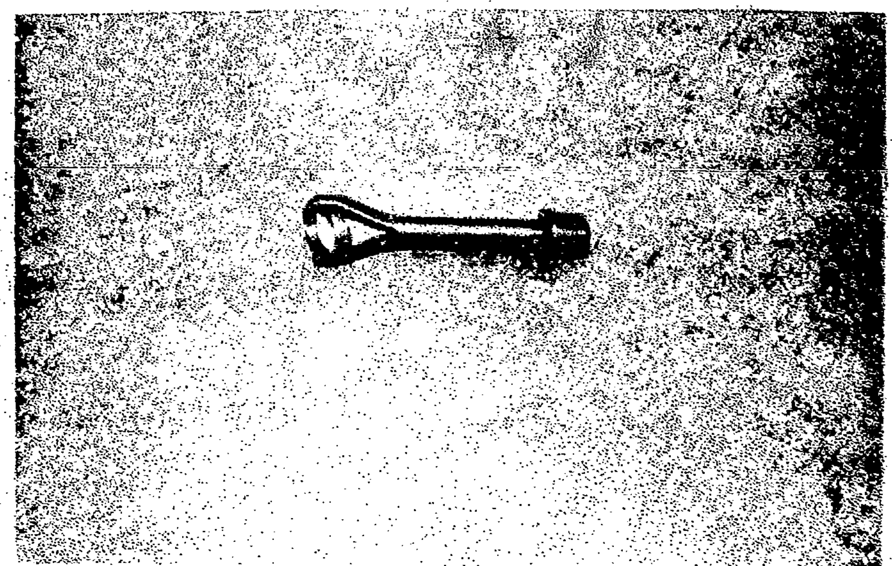


Fig. 20. Universal Gimbal

The gimbal is constructed from a piece of 3/8 inch plumbing pipe, 6 inches long, split down the center and spread on one end, thus forming a yoke. A ring, 3/8 inch long, cut from a 1.25 inch diameter aluminum tube, is bent slightly elliptically and fastened with a minor axis of the oval inside the yoke. The length of the major axis is the inside diameter of the 1.5 inch diameter tube used for the probe body. The other end of the 3/8 inch pipe is threaded with standard plumbing threads and screwed into a 3/8 to 1/2 inch pipe coupling. This pipe coupling is epoxy-glued in

the nose of the main case. Thus the probe or gimbal can be replaced when necessary by simply unscrewing the gimbal. The gimbal yoke can be mass produced by casting. The pipe coupling can be replaced by a threaded boss in the main case, making manufacture easier and less expensive.

The main case is cast in one piece from fiberglass. A lathe turned wooden plug is used as a form on which one eigth inch of fiberglass is wrapped. After the case is cured, fin axle bearing ports (.75 inch diameter) are drilled as shown in Appendix A. A fifth port is drilled in the nose to accept the pipe coupler by which the gimbal attaches. The case is placed on top of the BDU-33 and epoxy-fill is poured in the top hole. This forms a built up, form fitting attachment ring for the case to bomb connection. A coating on the BDU-33 prevents the epoxy from sticking to the bomb. The bottom of the main case is slotted as shown in Figure 21 so that it can be drawn up by a hose clamp and provide a strong attachment of the guidance unit to the BDU-33. An alternate case design which will be used on future models is described on page 46.

The signal from the detector is transported thru the hollow gimbal to the amplifier by a small diameter coaxial cable. The amplifier and pulse stretcher are made up on two 3.8 inch diameter circular bread boards, as shown in Figure 22. These

boards occupy the front two inches of the guidance case. The amplifier-pulse stretcher operates as described on pages 19 and 20.

Fig. 21. Main Case

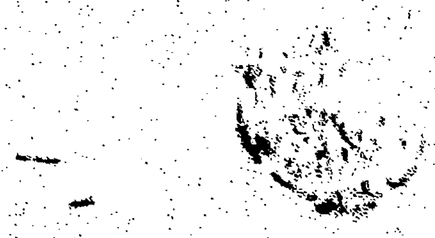


Fig. 22. Amplifier-Pulse Stretcher Circuit

These circuits can easily be reduced to one board and thereby reduce the length of the guidance unit main case by $1\frac{1}{2}$ inches. This circuit has been successfully tested under a temperature range of -50°C to 150°C. The cost per channel is about $12. Thus the four channels cost $48 when the required parts are purchased in small quantities. There is an alternate circuit, described on page 48, which was designed too late to be placed in this prototype. It is more compact and less expensive (about $7 per circuit).

The signal leaving the pluse stretcher was utilized to turn on the power transistor. The power transistor closes the circuit and provides current to the pull type solenoid. When this solenoid pulls in, it rotates the guidance fins into the relative wind. The solenoids (Figure 23) are manufactured by GUARDIAN (No 28 intermittent 6 VDC 1.6 amps) and cost $3.39 each when purchased in small quantity. They provide $1\frac{1}{2}$ pounds of holding force when activated.

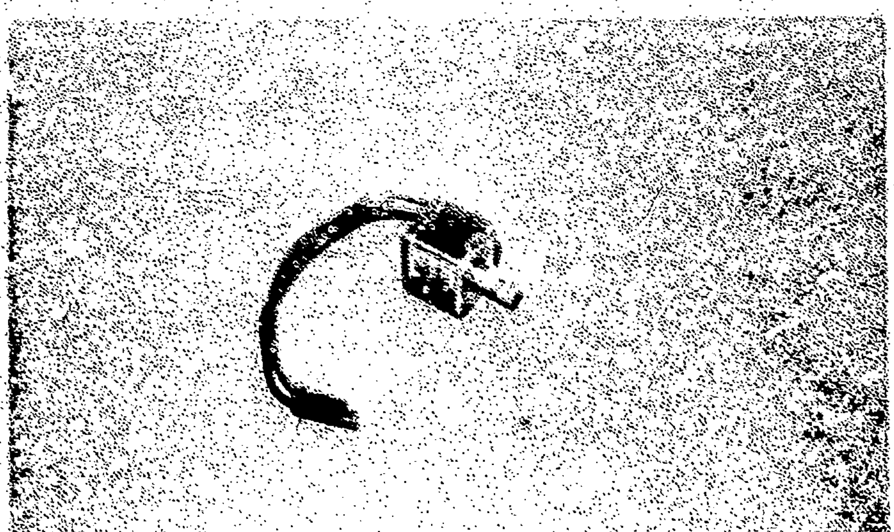


Fig. 23. Guardian Solenoid

Two solenoids are mounted facing each other on a frame as shown in Figure 24, and operate as described on page 19.

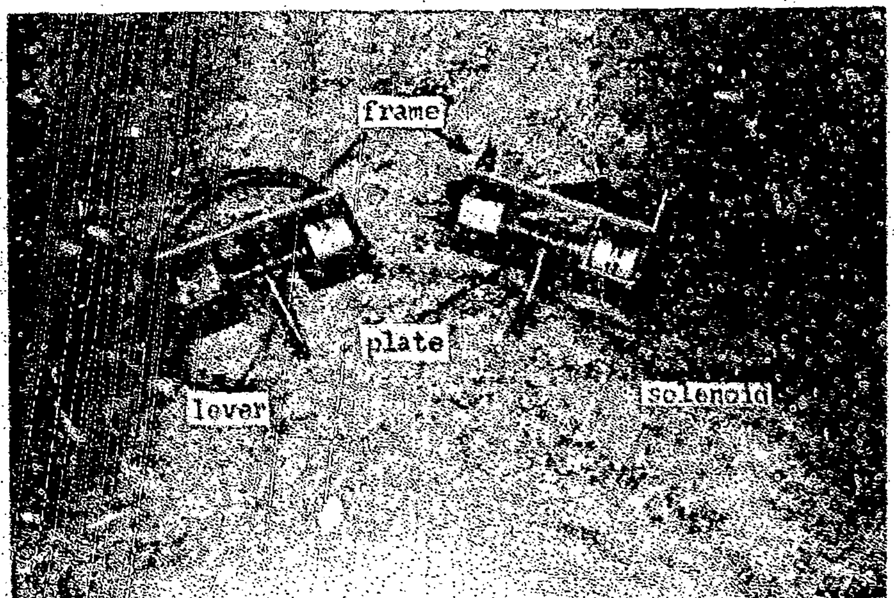


Fig. 24. Fin Power Package

This power package is mounted so that the axes of the solenoids are at right angle to the fin axle which it drives. The two solenoid shafts are held together by rivets thru a small plate. When the fins are not activated, light springs (.1 lb at full compression) mounted around the solenoid shafts provide an automatic fin centering mechanism. The lever for rotating the axle is attached to the plate as shown in Figure 26.

Thus as the solenoid shaft pulls back and forth the lever is free to rotate at the point where it connects with the plate. The mounting frame is slightly different for the front and rear solenoids. This difference makes it easier to mount

them in the main case due to the case taper. This taper was necessary to facilitate removal of the case from the wooden form.

The fins were constructed of 1/16 inch 2024 aluminum. They were bent up 1/4 inch on both long edges to provide rigidity under loading. As an added benefit, this bend also reduces aerodynamic curl by providing a fence for the air flow. The leading edge of the fin was sharpened to improve the stability and air flow characteristics. The fins fit into a slot in the axle and are held in place by two screws as shown in Figure 25. Pop rivets are suggested instead of screws for mass production.

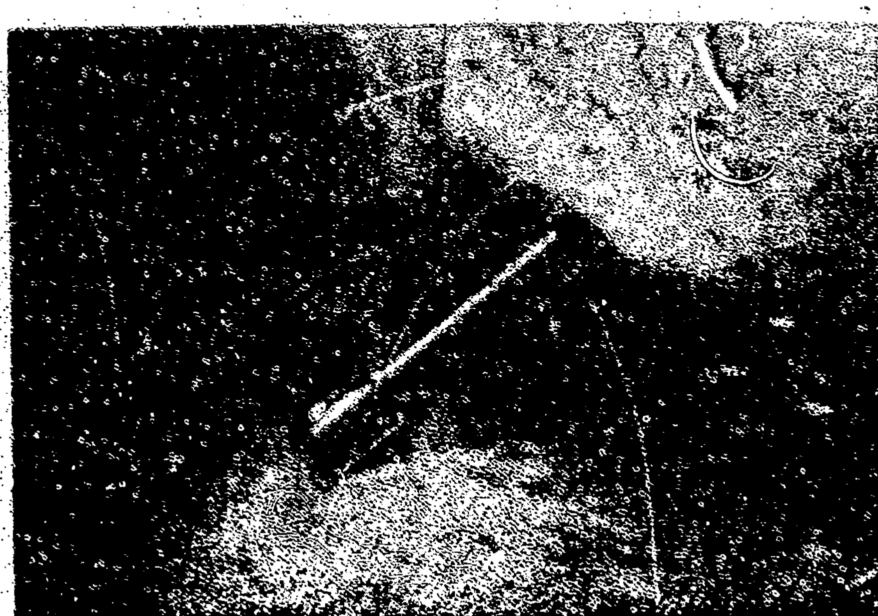


Fig. 25. Fins Mounted on Axle

The necked-down portion of the lever slides into a hole in the middle of the fin axle and is held in by the arrangement inside the case. Shown on the axle are two self aligning bearings. It has been experimentally determined that cheap (10¢ to 20¢) ball bearings can replace the more expensive self aligning bearings shown in Figure 26.

The combined power package and fin assembly are shown in Figure 26 as they would be mounted in the main case.

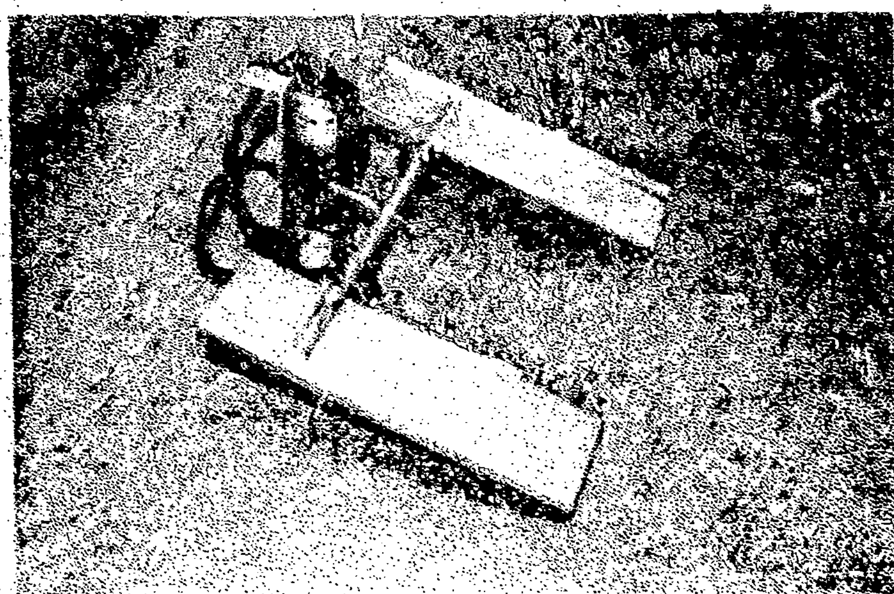


Fig. 26. Assembled Power Package & Fin Assembly

The power to drive the solenoids and the amplifier-pulse stretcher circuit is provided by a nine volt lantern battery, which drops under load and maintains a steady six volts. Currently this prototype provides space for a spotting charge in the BDU-33 tail section. The guidance unit is coupled to the BDU-33 by use

of a 4 inch hose clamp. This method is simple, rugged and inexpensive.

The total cost of this guidance unit is shown in Table 1. Some part costs must be estimated as those parts were constructed from basic material.

Batteries	$ 2.00
Holder	.50*
Lens	1.25
Filter	9.00
Detector	65.00
Probe	1.00*
Gimbal	1.00*
Main Case	2.00*
Circuits	48.00
Solenoids	13.56
Mounting Frame	.50*
Fins & Axle	.50*
Bearings	.50*
Total	$144.81

*Estimated

Table 1. Cost Estimate

The two main cost items are the detector and the circuits. The alternate circuit (page 49) would reduce this cost from $48 to $30. The use of ram air for power would reduce the cost about $10 (page 43). Labor will, of course, be an added cost. However, this unit was designed to be manufactured with low labor costs.

This completes the manufacture of the BDU-33 laser guidance unit. The completed unit is shown in Figures 27, 28, and 29.

Fig. 27. Head on View

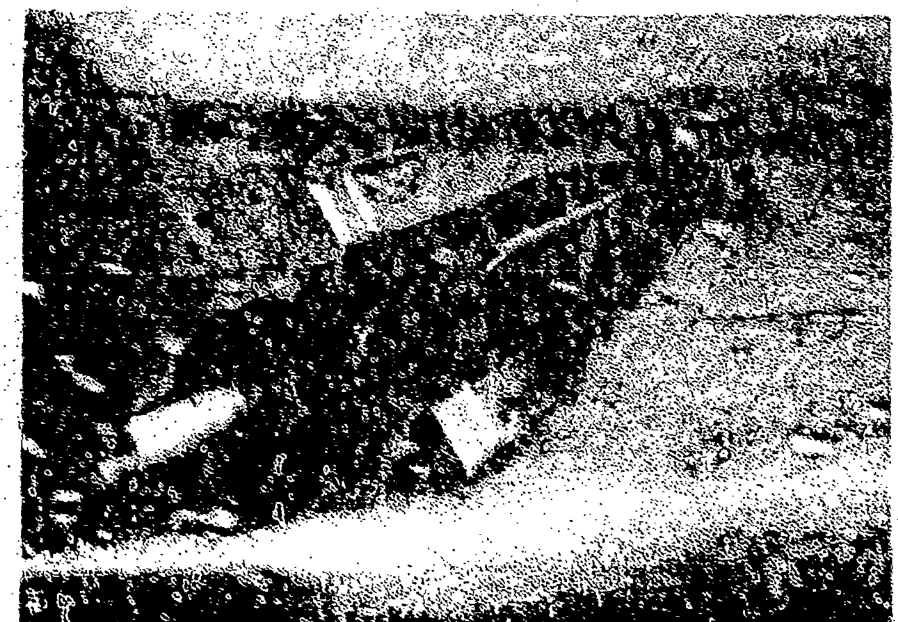


Fig. 28. Front Quartering View

Fig. 29. Rear Quartering View

V. Alternate Methods

A promising alternate method was considered for providing power for this guidance unit. Lack of time and sufficient data prevented its full exploration. This method is presented here as a possible means for reducing the cost of this guidance unit.

The idea is to utilize the dynamic energy in the relative wind passing the falling bomb to power the guidance fins. This would require converting the passing wind into ram pressure as shown in Figure 30.

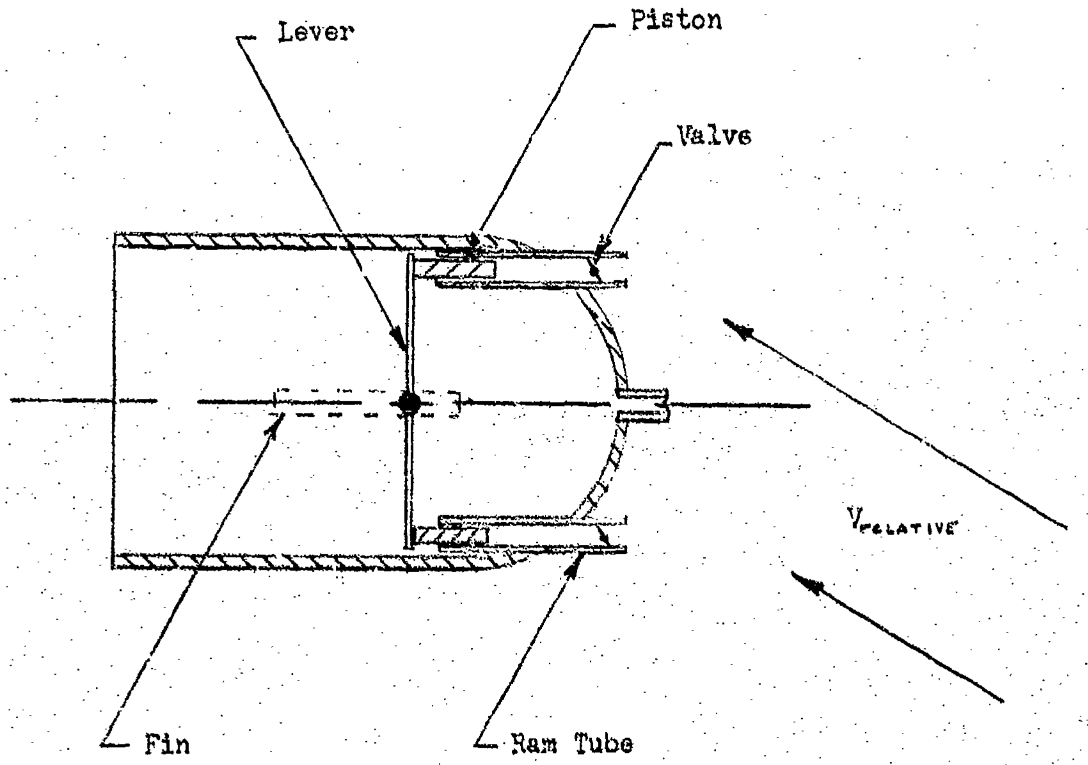


Fig. 30. Ram Air Powered Fins

The ram pressure would be controlled by solenoid actuated butterfly valves in the leading part of the ram air tubes. The pressure obtainable on one square foot of surface by air passing at 760 ft/sec may be calculated as follows. (Ref 7:54)

$$P = WV^2/g \tag{14}$$

$$P = (.002)(760)^2 \tag{15}$$

$$P = 1155 \text{ lb/Ft}^2 \tag{16}$$

Therefore, if the cross sectional area of the ram air tube is one square inch, one could achieve 8.01 lbf on a piston in that ram air tube. There will be some loss due to changes in alignment between the relative wind velocity vector and the ram air tube as the bomb falls. Other loss will occur due to a decrease in the effective ram tube cross sectional area as the boundary layer builds up. However, even if the losses were 50% (ie, if only 4 lbf were useable), sufficient force is still available to power the fins.

One method to reduce the misalignment between the ram air tube and the relative wind is to make the leading portion of the tube flexible and attach it to the probe assembly as shown in Figure 31.

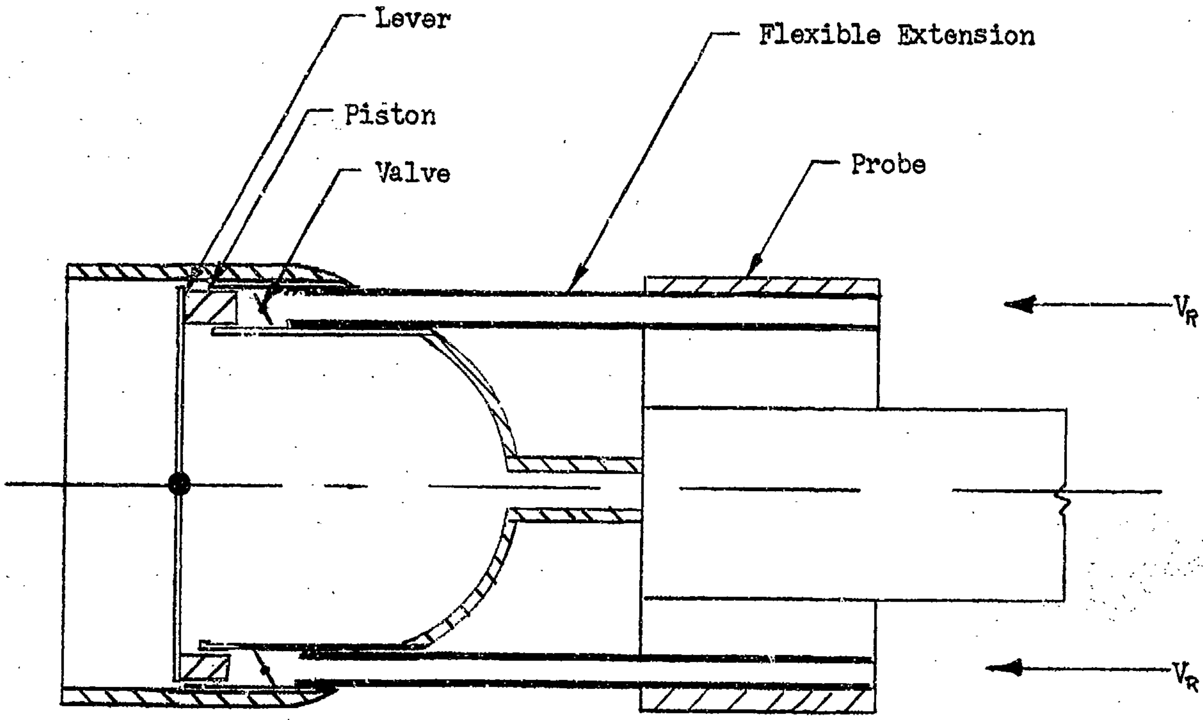


Fig. 31. Alignment Method

Since the probe is always aligned with the relative wind the ram air tube will then always be pointed in the proper direction. The ram tube, from the probe to the main guidance body, would be flexible (ie, plastic) and would slide in and out of the ram tube in the main guidance section as necessary, to allow the probe to align with the relative wind. There could be some binding problem here but graphite or some similar lubricant should solve this problem. This idea was not followed up due to a lack of data on the magnitude of the misalignment one could expect between the ram tube and the relative wind. Bomb mounted film taken during the fall of a full scale laser bomb indicated that very large oscillations can be expected. Wind tunnels were not available at the time to test a model and no available sources

could make a prediction of the magnitude of the misalignment. Should this method prove useable the cost reduction would be around 10% and the unit could be made about six inches shorter. Also maintance and storage costs could be reduced.

The third idea revolves around building a main case that would provide for easier repair or mass production. Instead of being fabricated entirely from fiberglass, this new main case would be composed of a 4-inch diameter aluminum tube with a fiberglass cap. The cap and the tube would be joined by epoxy glue and machine screws (Figure 32).

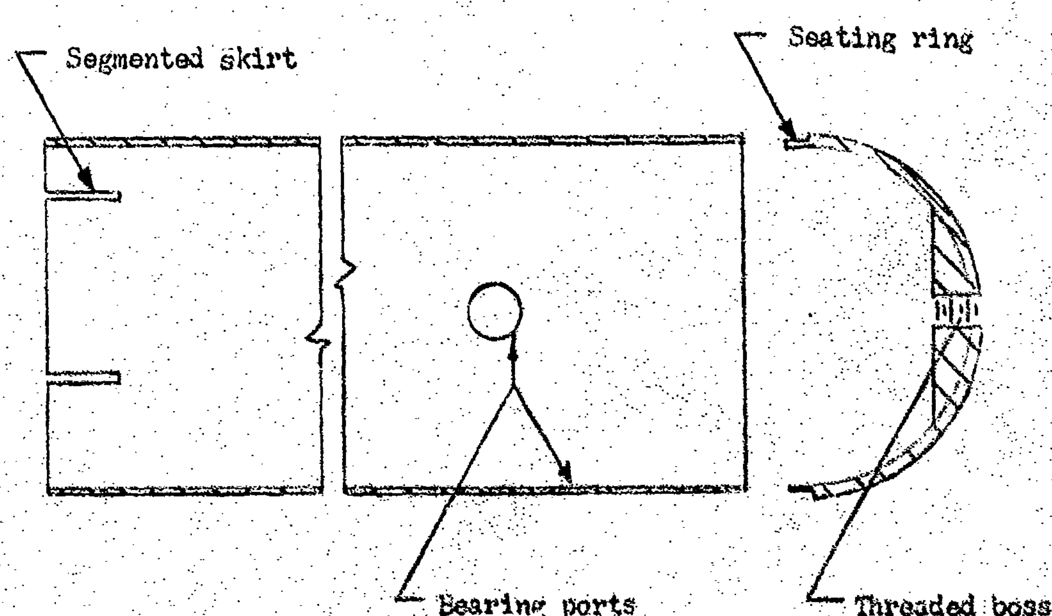


Fig. 32. Main Case

This new design has the advantage of providing for easy access to the electronic package for assembly or repair. Also,

the all fiberglass case has a 1° longitudinal taper to facilitate its removal from the wooded form. This taper proves to be a problem when fitting the solenoids into the case. To be able to assemble or disassemble the guidance unit from either end of the main case would be a distinct advantage. The price should be about the same as for the all fiberglass case.

A new, lower cost amplifier circuit (Figure 33) was developed too late to be included in this prototype. It utilizes more components but the individual components are all lower cost items. This circuit, not including the detector, cost about $6.00 when built from singly purchased components. This amplifier has 50% more gain than the one now in use. This was accomplished by decoupling each stage of amplification and thus preventing feedback and oscillation. The circuit also allows some degree of amplification selection through a 5K gain control pot. This adds flexibility for the detector substitution. This amplifier could be coupled either into the pulse stretcher circuit already utilized in the bomb or coupled into the one-shot multi-vibrator described in Figure 34. The pulse stretcher circuit costs about $3.50, but can be replaced by a one-shot multi-vibrator which can be built for $1.00 (2N2222 and 2N2219 cost 18¢). The new amplifier and one-shot milti-vibrator could be built for $7.00.

Should all these ideas prove feasible, the guidance unit would be smaller, simpler and less expensive by about 25%.

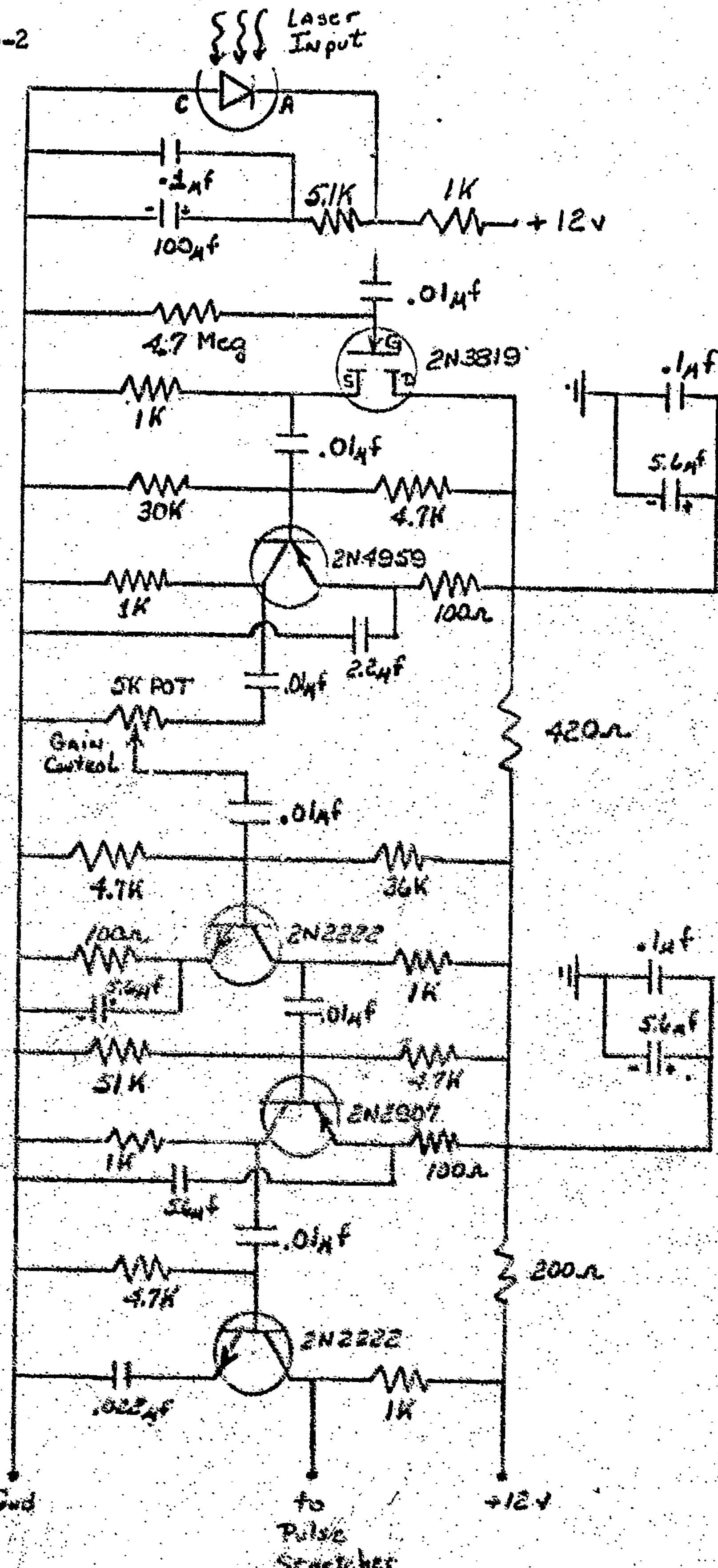


Fig. 33. Amplifier Circuit

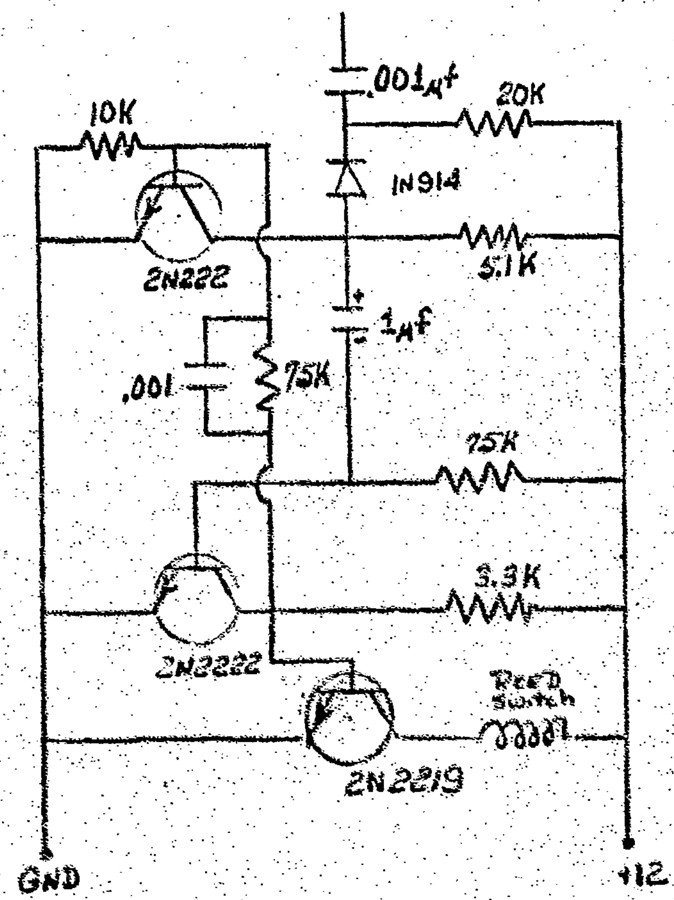


Fig. 34. One-Shot Multi-Vibrator Circuit

VI. Summary

As with any new weapon, training requirements should be considered along with the weapon's development. The man- machine interface will, to a great extent, govern the reliability of the weapon under field conditions. The idea for a low cost practice laser-guided bomb was conceived because training with the real device was not economically feasible. The guiding principle behind building the prototype was faithful simulation of the characteristics of the full scale weapon.

Section II detailed the training advantages obtained when utilizing the prototype. Valuable training criteria such as judgment of crosswinds, judging reflection patterns, and real time feedback for teaching new techniques can be gained when the laser guided practice bomb is utilized.

Section III explained how the flight characteristics of the full scale weapon were engineered into the prototype. Items such as a 24° field of view, "Bang-Bang" guidance, and a 2 g maximum guidance correction during flight were incorporated into the prototype to realistiually simulate the full scale weapon. Basic calculations were used to determine the feasibility of building such a device.

Section IV dealt with the materials and construction utilized in manufacture of the guidance unit. The objective behind manufacture were ruggedness, simplicity, and dependability. There

was a concerted effort made to keep all materials easily obtainable and bomb fabrication uncomplicated. Design of the electronic subsystem within cost limitations proved to be the biggest barrier. The fin power is provided by an off-the-shelf GUARDIAN 6 volt solenoid. The entire guidance kit can be fabricated from parts costing less than $140.

As might be expected, new and better ideas concerning the manufacture of the prototype emerged during the building process. Unfortunately, time did not allow further exploration of these ideas. Section V records these concepts for future exploration. A guidance unit powered by ram air pressure and a better main case are detailed. Hopefully these ideas can be expanded upon in the future.

This laser-guided practice bomb should be an aid in providing initial and recuring training to our laser bomb equipped tactical forces. Future availability will depend on programs subsequent to this report.

Bibliography

1. Carroll, J.M. Design Manual for Transistor Circuits. New York: McGraw-Hill, 1961.

4. Fowles, G.R. Introduction to Modern Optics. New York: Holt, Rinehart & Winston Inc., 1968.

5. Harmon, W.W. and Trucal, J.G. Pulse, Digital, and Switching Waveforms. New York: McGraw-Hill, 1965.

6. Heard, H.G. Laser Parameter Measurements Handbook. Wiley & Sons Inc., 1968.

7. Hudson, R.G. The Engineers Manual. New York: Wiley & Sons, 1944.

8. Jones, R.T. and Cohen, D. High Speed Wing Theory. New York: Princeton University Press, 1960.

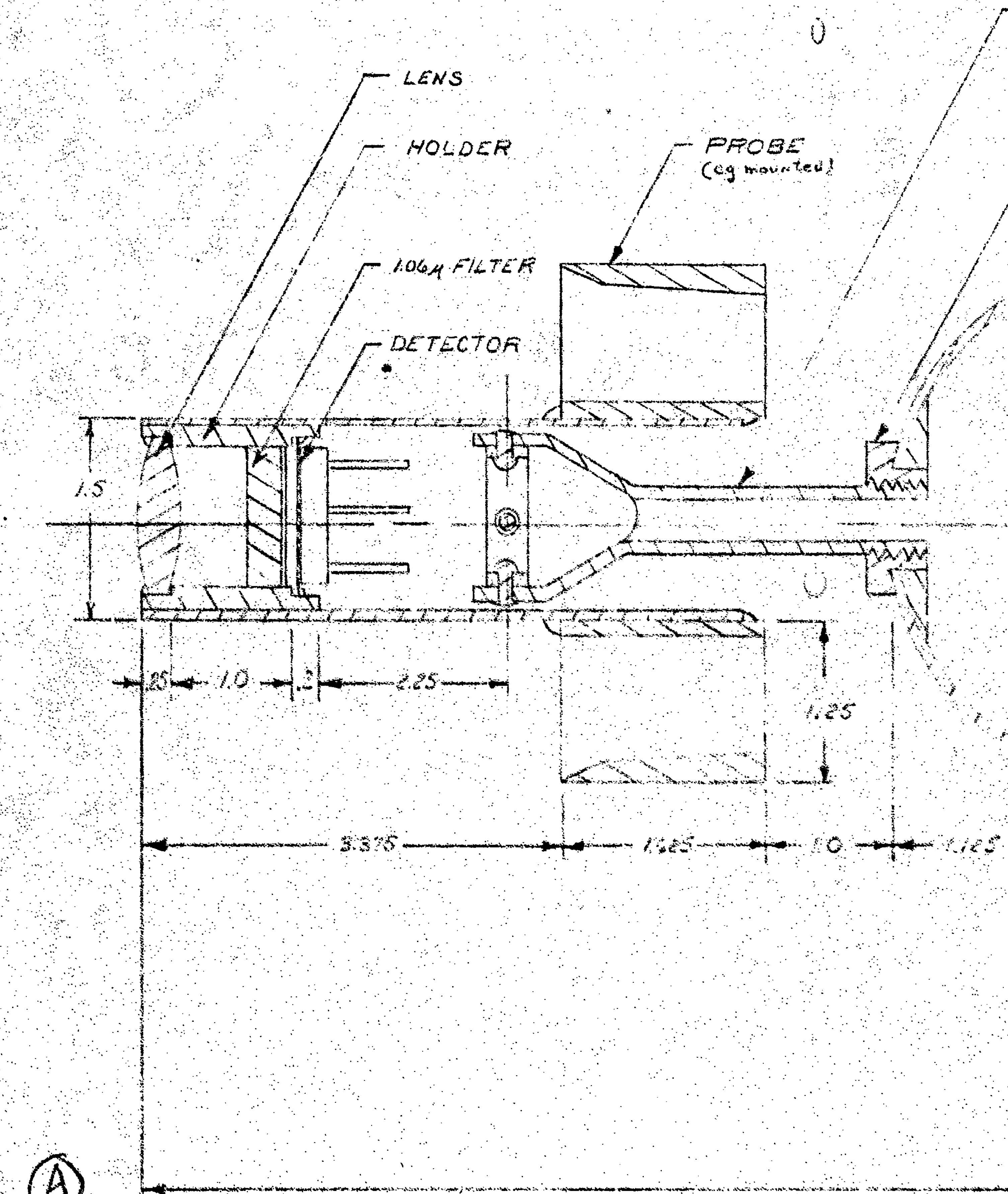
9. Klein, M.V. Optics. New York: Wiley & Sons Inc., 1970.

10. Kuethe, A.M. and Schetzer, R.L. Foundations of Aerodynamics. New York: Wiley & Sons Inc., 1959.

12. Reid J.A. Evaluation of the Extended Wing [illegible]. ADTC-TR-71-53 Eglin AFB, Florida, May 1971.

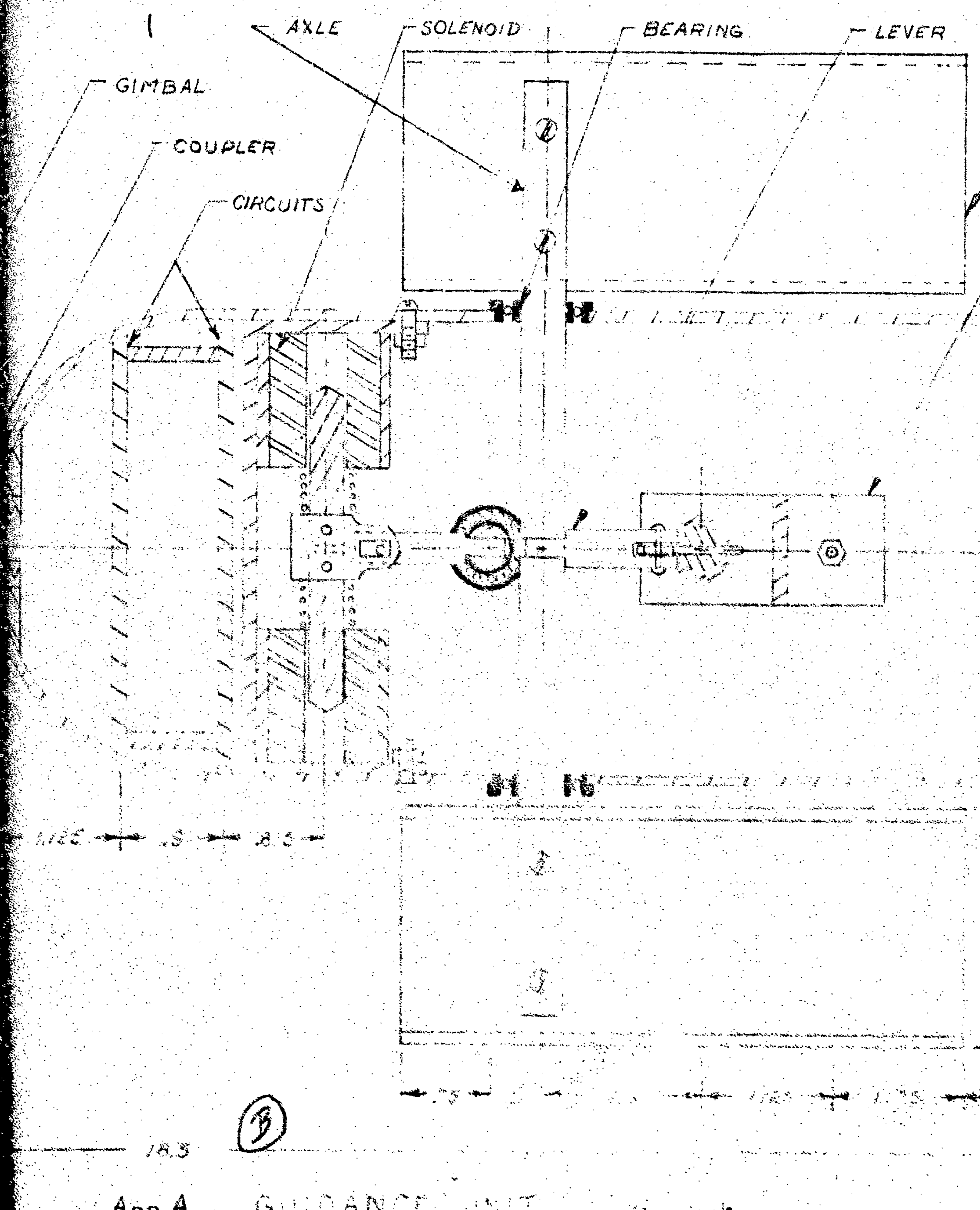
13. Schawlow, A.L. Lasers and Light. San Francisco: W.H. Freeman and Company, 1969.

APPENDIX A

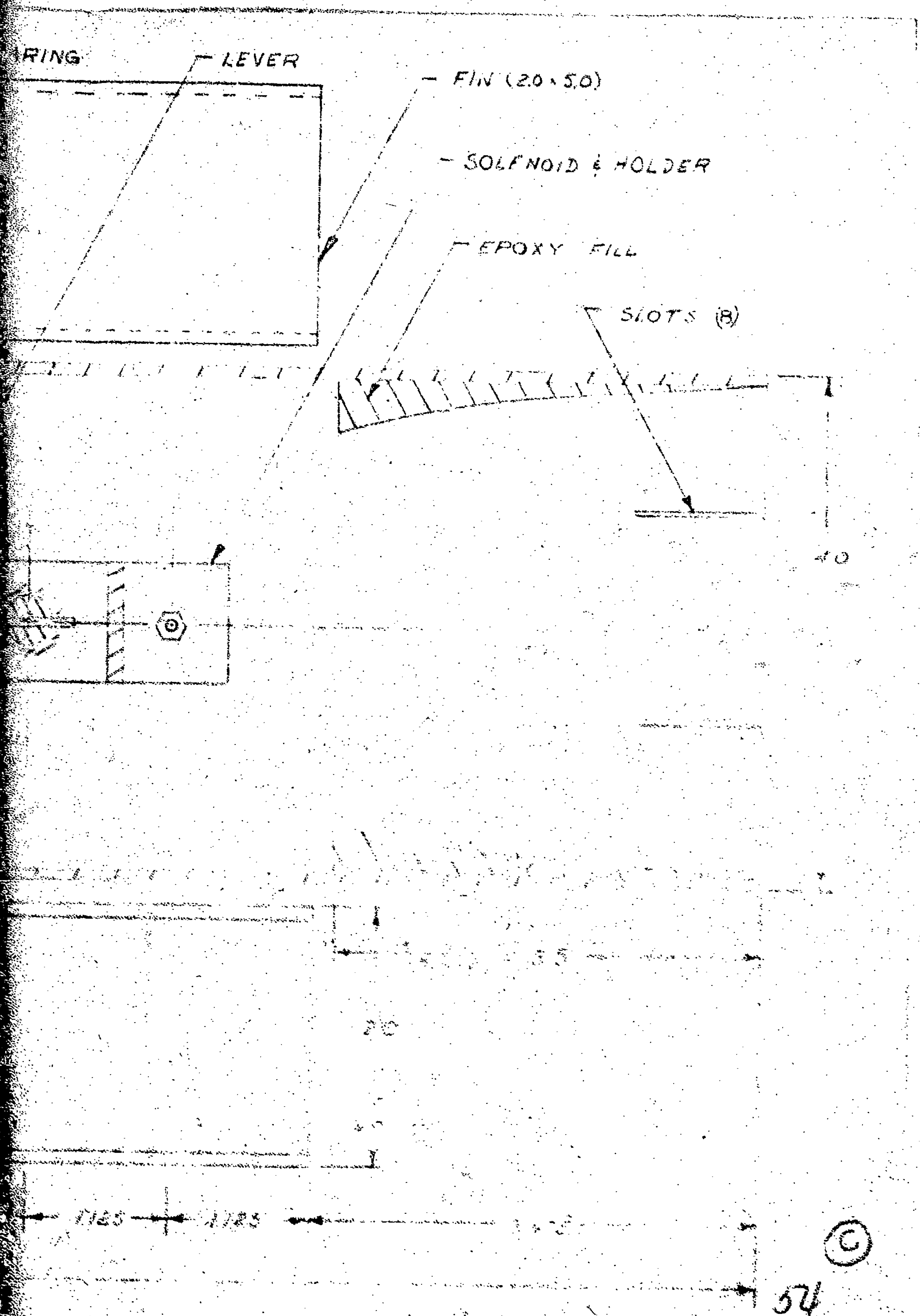


LENS
HOLDER
PROBE
(cg mounted)
1.06μ FILTER
DETECTOR
1.5
.25
1.0
.3
2.25
1.25
3.375
1.125
1.0
1.125

(A)



App A. GUIDANCE UNIT


RING
LEVER
FIN (2.0 x 5.0)
SOLENOID & HOLDER
EPOXY FILL
SLOTS (8)
4.0
3.5
2.0
.1125
.1125

Appendix B

Theoretical Spot Size

Using the Airy disk relationship:

$$d = 2.44 \frac{f\lambda}{D}$$

$$d = \frac{(2.44)(26)(1.06 \times 10^{-3})}{25.5}$$

$$d = 2.64 \times 10^{-3} \text{ mm}$$

Vita

William C. Ayers was born 13 July 1941 in Nashville, Tennessee and moved extensively during his early years. In 1963 he graduated from the Air Force Academy. Following graduation, he attended pilot training at Webb AFB, Texas, and was assigned as a T-38 instructor at Williams AFB, Arizona. In 1968, after completing some 2500 hours flying time, he was reassigned to fly F-4's at George AFB, California. Cam Rahn AB, Vietnam followed next where he flew combat until Cam Rahn AB was closed in March 1970. Upon the closing, Captain Ayers was reassigned to 7th AF (Tan Son Nhut) while continuing to fly combat from Phu Cat AB, Vietnam. During his tour he flew a total of 128 missions in SVN, Laos, Cambodia, and 3 in NVN. Following Vietnam he was reassigned to F-4's in Misawa, Japan with numerous TDY's to Korea. Misawa was closed in May 1971 and Captain Ayers was assigned to AFIT residence school, Dayton, Ohio in the Graduate Air Weapons program.

Permanent Address: Capt. William C. Ayers
P.O. Box 229
McLean, Va. 22101